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16. ABSTRACT

The research was aimed at improving the filtration and incineration characteristics of primary activated sludge by the addition of pulverized coal prior to the dewatering step. Various doses of coal were added to the sludge in the range of 0.1 to 0.4 kg coal/kg dry sludge solids. The results showed dramatic improvements in cake solids content and heat value of the dewatered sludge cake. At a coal dose of about 0.11 kg coal/kg dry sludge solids, the moisture content and the heat value of solids in the cake were balanced to permit autogenous combustion. The filter yield (corrected for chemicals and coal) was increased slightly at the coal dose required for autogenous combustion.

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Improving sludge incineration and vacuum filtration with pulverized coal

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In 1975 over 1 million dry tons of wastewater sludge were disposed of through incineration in the United States. This 1 million tons constituted approximately one-fourth of the total sludge production in the U. S. in 1975. Increases in sludge production and pressures on alternative disposal techniques indicate that sludge incineration will continue to grow both in absolute magnitude of the sludge processed and relative share of total sludge disposal.

Properly designed and well-controlled sludge combustion can be an effective, environmentally acceptable sludge disposal practice. However, incineration is costly. Aside from the installation and maintenance costs for combustion and air pollution control equipment, the major cost associated with sludge incineration is that of auxiliary fuel.

The need for supplemental fuel arises because secondary sludge, even after mechanical dewatering, contains too much water to permit autogenous combustion. While dry wastewater solids are an excellent fuel, combustion of sludge cakes with moisture content in excess of 70 percent requires the input of supplementary fuel into the combustor. Most often, the supplemental fuel used is natural gas or light fuel oil. The cost of these fuels to the treatment plants has risen significantly in the past 2 years while the availability of the fuels has diminished substantially. Most treatment plants have been unable to obtain guaranteed contracted sources of supply. While the increasing fuel cost is painful, the uncertainty in supply is potentially a more serious problem. Under present conditions, without supplemental fuel, treatment plants simply cannot dispose of their sludge. Thus, there exists a need to eliminate or, at least, reduce the demand for costly auxiliary fuel in wastewater sludge incineration.

Auxiliary fuel demand can be reduced in two ways:

1. Increase the solids content of the sludge feed to the incinerator. This can be accomplished through improvement in conventional dewatering techniques, such as vacuum filtration, or through application of newer, more effective dewatering techniques, such as pressure filtration.
2. Enhance the fuel value of the sludge solids.

APPROACH TO RESEARCH

The research described in this discussion attacked the problem of auxiliary fuel consumption from the aspects of increased solids content and enhanced fuel value. The technique used in the study was the addition of pulverized coal to the liquid sludge prior to vacuum filtration.

The basis for expecting improved vacuum filtration performance with addition of pulverized coal can be found in a previous study that reported significant increases in both filter yield and final cake solids content with the addition of sludge incinerator ash to the liquid sludge prior to vacuum filtration.[1] While the addition of ash did improve the vacuum filter performance, it also decreased the fuel value of the resultant filter cake because of the addition of the thermally deficient ash to the incinerator feed. The addition of pulverized coal offered the prospects of a similar improvement in filtration with a complementary increase in cake fuel value. Ideally, the coal addition would:

1. Increase the vacuum filter yield, or throughput.
2. Increase the resultant sludge cake solids content.
3. Replace or reduce the amount of conditioning chemicals required for filtration of

TABLE I. Energy required for sludge cake. (Basis: 1 metric ton dry solids).

Cake Moisture: Solids Ratio	kg Water/ Metric Ton Dry Solids	Energy Req. to Drive Off Water (kg·cal/metric ton × 10^{-6})	Energy Provided by Sludge Solids (kg·cal/metric ton × 10^{-6})	Auxiliary Energy Req. (kg·cal × 10^{-6})	Liters of #2 Fuel Oil for Auxiliary Requirement
95 : 5	19 000	26.9	4.05	22.9	2 380
90 :10	9 000	12.7	4.05	8.65	899
85 :15	5 667	8.02	4.05	3.97	413
80 :20	4 000	5.66	4.05	1.61	167
78.5:21.5	3 651	5.17	4.05	1.12	116
75 :25	3 000	4.25	4.05	0.20	21
74.1:25.9	2 861	4.05	4.05	0	0
70 :30	2 333	3.30	4.05	Autogenous	—
65 :35	1 857	2.63	4.05	Autogenous	—

Note: Multiple hearth incinerator at 427° C stack gas temperature and 75 per cent excess air. For each kg of water, 1415 kg·cal are required to evaporate the water, raise the temperature to the stack gas requirement and compensate for sensible heat losses from the stack and convective heat losses through the incinerator walls.

secondary sludge (as did the addition of sufficient quantities of ash).

4. Replace or reduce the amount of high priced natural gas or fuel oil required for supplementary fuel in the sludge incineration operation.

INCINERATION REQUIREMENTS

To establish a foundation for our discussion of auxiliary fuel conservation, the quantitative need for this fuel in sludge combustion must first be established. Table I shows the quantity of auxiliary fuel required for different cake moisture values to maintain a multiple hearth incineration system at 427°C (800°F) off-gas temperature and 75 percent excess air. At a point corresponding to 25.9 percent cake solids the heat required to drive off the moisture equals the heat provided by the sludge solids. At this point the process is autogenous; that is, no additional fuel input is required. For the 760°C (1 400°F) and 75 percent excess air situation, the cake solids content needed for autogenous combustion is calculated at 29.5 percent.

These calculations are based on a sludge which has a heat value of 5 828 kg-cal/kg (10 500 Btu/lb) of dry volatile solids. At 70 percent volatile content this value corresponds to about 4 052 kg-cal/kg (7 300 Btu/lb) of dry sludge solids.

The values in Table I were calculated on a theoretical basis for a sludge cake containing only water and sludge and have been supported reasonably well by field data.[2, 3] However, in most operations the incinerator feed normally contains some filtration aid material such as lime and ferric chloride, which is usually a noncombustible. The fuel value of the sludge cake decreases proportionately with the addition of the noncombustible filtration aid material. In this discussion of incinerator requirements we find that three components of the sludge cake are important: cake moisture, cake combustibles, and cake noncombustibles. Therefore, to optimize the incineration process, the feed material must be a balance of these three components. The goal of the pilot-scale testing with coal addition was to determine by actual filtration experiments the proportion of coal that must be added to sludge so that a proper balance is obtained and the cake will be autothermic.

FILTER LEAF TESTING

The pilot plant work conducted on pulverized coal addition was a progression from previously completed bench-scale filter leaf testing. The bench-scale experiments established that pulverized coal additions in the range of from 10 to 40 weight percent of dry solids produced higher cake solids contents and autogenous sludge cakes with no decrease in filter throughput. The filter leaf testing is summarized in a separate publication.[4]

PILOT PLANT TESTING METHODS AND MATERIALS

The small pilot system was set up at the EPA Pilot Plant in Lebanon, Ohio. Sludge for the study was obtained from the Lebanon Wastewater Treatment Plant adjacent to the EPA research pilot plant. The sludge used in this study was a blend of primary and

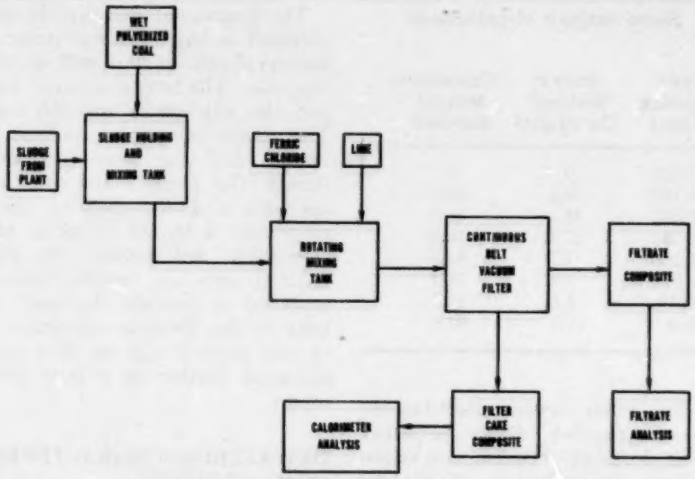

FIGURE 1. Flowsheet for pilot plant sludge filtration.

waste activated sludge mixed in a ratio of 1:1 on a dry solids basis. The average as received solids concentration was 2.2 percent. Figure 1 is a diagram of the system which consisted of a sludge holding tank (where the activated and primary sludges were mixed and the pulverized coal added), a rotating mixing tank for mixing the ferric chloride and lime with the sludge, and a pilot scale vacuum filter. The mixing tank was a small horizontal drum with baffles inside to gently mix without shearing the sludge particles. Ferric chloride and lime were pumped into the mixing drum with the sludge feed. From the mixing drum the mixture of sludge, coal, and conditioning agents dropped by gravity into the vacuum filter vat. The vacuum filter was a small 0.28 m^2 (3 sq ft) continuous belt machine with a polypropylene monofilament media. The filter was operated at 300 to 500 mm Hg (15 to 20 in Hg) vacuum pressure and the drum was rotated at 4 minutes per revolution. Other cycle times were used only periodically. Filtrate was collected continuously and composited after each run for analysis. The filter cake was composited after each run. To determine the thermal characteristics of the filter cake, the samples were dried at 104°C and analyzed for heat content in an adiabatic calorimeter.

For each run, vacuum filtration was continued for 1 to 2 hours. This time interval was considered adequate to allow the filter to achieve peak production of filter cake. The pulverized coal was added directly to the liquid sludge in a batch system prior to filtration.

The characteristics of the sludge feeding system were such that some of the coal was lost before the sludge/coal mixture was introduced to the vacuum filter. A subsequent discrepancy between calculated and experimental data was reconciled through a regressive normalization procedure. The normalization exercise yielded experimental results that conformed so closely to the predicted values that confidence in the reported data has not been diminished. The normalization rationale and procedure is described fully in Appendix A.

PROPERTIES OF EXPERIMENTAL MATERIALS

Before the results of this study can be described, the properties of the two substances most important in the research, the sludge and the coal, must be discussed. The sludge showed no unusual physical character-

TABLE II. Properties of experimental materials.

Property	Coal	Sludge
kg·cal/kg dry volatile solids	7 881	5 828
Volatile solids (%)	93.6	70
kg·cal/kg dry solids	7 382	4 090
Sulfur (%)	0.60	0.60

TABLE III. Sieve analysis of pulverized coal.

Tyler Mesh	Sieve Opening (mm)	Percent Retained (by weight)	Cumulative Percent Retained
2	9.525	0	0
14	1.180	20.0	20.0
28	0.600	28.5	48.5
65	0.212	27.7	76.2
100	0.150	7.7	83.9
200	0.075	7.2	91.1
400	0.038	6.0	97.1
	Pan	2.7	99.8

istics except that solids content after thickening was low—2.2 percent. Other properties of the coal and sludge of importance in establishing the heat of combustion of the incinerator feed are presented in Table II. The sludge was a blend of raw and waste activated sludge which had been conditioned with 10 percent lime and 5 percent ferric chloride before filtration. As Table II indicates, the dry sludge solids averaged 70 percent volatile solids with 30 percent noncombustible ash. The calorimeter analysis showed that 1 kg of dry filter cake (no coal) produced 4 079 kg-cal (7 370 Btu/lb) upon ignition, corresponding to 5 828 kg-cal/kg volatile solids (10 500 Btu/lb volatile solids). Analysis of the coal used in this study showed that 1 kg of dry coal produced 7 382 kg-cal/kg (13 300 Btu/lb) upon ignition. This type of coal (Pennsylvania mine-run bituminous) was high grade coal with an ash content of only 6.3 percent.

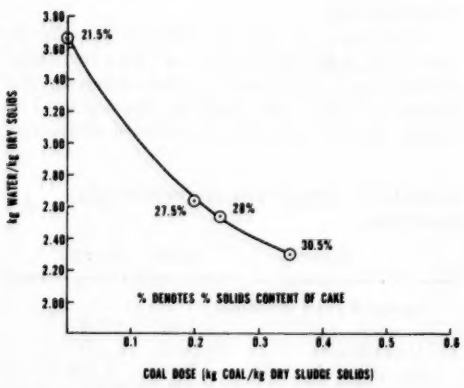

FIGURE 2. Moisture content of filter cake.

The bituminous coal used in this study was obtained in bags and was ground in a rigid-horizontal-axis hammer mill at 3 600 rpm before use. The largest nominal size allowed to pass the mill grates was 9.5 mm (.37 in.). The results of a sieve analysis on the pulverized coal are given in Table III. Although the particle size of the coal does not have a direct effect on the incineration properties, it should definitely impact sludge filterability and possibly the cake moisture content, with the smallest particle size coal expected to produce the most favorable results in the filtration operation. The effect of coal particle size on filter performance is discussed further in a later section of this report.

DEWATERING CHARACTERISTICS WITH COAL ADDITION

When pulverized coal was added to the sludge in doses from 0.1 to 0.4 kg coal/kg dry sludge solids, the dewatering results were excellent. Figure 2 describes the effect of coal addition on cake moisture content (kg water/kg dry solids). As can be seen from Figure 2, cake moisture content decreased significantly when coal was added to the liquid sludge prior to filtration. In terms of percent cake solids, the values ranged from 21.5 percent where no coal was added to 30.5 percent where 0.35 kg coal/kg dry sludge solids was added. As previously noted in Table I, a sludge cake with a solids content of at least 25.9 percent will combust autogenously in a multiple hearth furnance with 427° C (800°F) exhaust gas and 75 percent excess air.

The importance of adding the pulverized coal to the the sludge prior to filtration versus mixing the coal with the filter cake is demonstrated in Figure 3. This figure is a comparison of cake solids content produced in each case. The original cake solids with no coal added was 21.5 percent. Curve A represents the case where coal is added after the filtration process and then mixed with the cake. Curve B is the plot of cake solids content achieved by adding the pulverized coal prior to filtration. The figure shows that the solids contents for the cakes produced when coal is used as a filter aid are much higher than when coal is added after filtration. The significance of those differences can be emphasized if the increase in heat of combustion caused by coal addition is neglected and it is assumed that a 25.9 percent solids cake is

required for autogenous combustion. If the sludge is filtered with no coal, the result is 21.5 percent cake solids. To increase this cake to 25 percent solids by mixing coal with the cake (post filtration) requires 0.29 kg of coal/kg dry sludge solids. But if the coal is added to the sludge before filtration, the dosage required to obtain 25.9 percent solids is only 0.13 kg coal/kg dry sludge solids. This figure illustrates that the addition of coal to the sludge before filtration not only increases the cake solids simply by the amount of coal solids added, but also provides a boost to the dewatering mechanism in the filtration operation itself. The resultant cake solids content achieved is substantially higher than that obtained from simple addition of pulverized coal to the sludge cake.

THERMAL CHARACTERISTICS WITH COAL ADDITION

That the addition of pulverized coal results in a substantial decrease in moisture content with respect to sludge solids represents, in itself, a significant improvement in incinerator performance. The combustion chamber sees less total moisture in the sludge feed and, in effect, more fuel in the form of dry sludge solids per unit of moisture added. Overall supplemental fuel demand is reduced. While it was not verified in this study, it can also be assumed that the incinerator performance is improved by the thorough mixing of the pulverized coal with the sludge solids accomplished in the vacuum filter. This degree of mixing would not be obtained through the addition of lumped coal to the sludge cake.

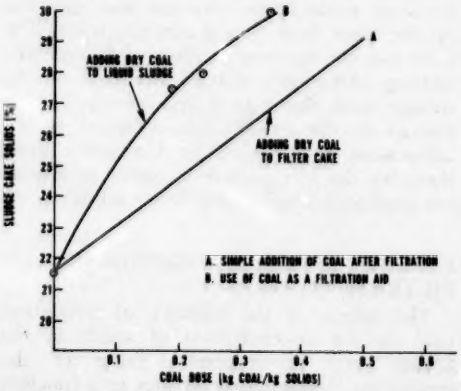
ADDING DRY COAL TO LIQUID SLUDGE
ADDING DRY COAL TO FILTER CAKE
A. SIMPLE ADDITION OF COAL AFTER FILTRATION
B. USE OF COAL AS A FILTRATION AID
SLUDGE CAKE SOLIDS [%]
COAL DOSE [kg COAL/kg SOLIDS]

FIGURE 3. Comparison of final cake solids.

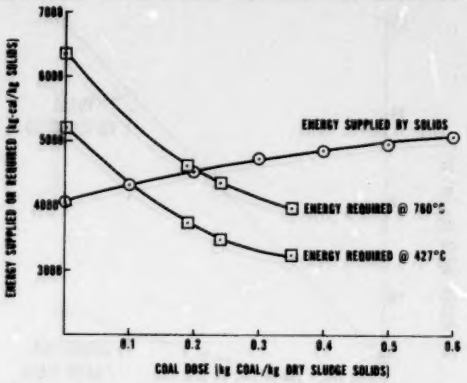

FIGURE 4. Energy requirements for incineration of filter cake containing 1 kg solids.

Additional benefits to the incineration process are realized through the heating value supplied to the sludge cake feed by the coal volatiles. As expected, sludge cake heating value increases in proportion to the coal dosage supplied to the sludge mixture.

The combined effects of the increased fuel value and decreased moisture content with pulverized coal addition are illustrated in Figure 4. Coal dosage is plotted on the abscissa while the ordinate displays the energy per kilogram of total cake solids. The curves sloping downward with increasing coal addition describe the energy required to sustain combustion in a multiple hearth incinerator at 427°C (800°F) and 760°C (1 400°F) (75 percent excess air) exhaust gas temperatures. The negative slope is accounted for by the aforementioned decrease in cake moisture content with increasing coal addition.

The curve which slopes upward with increasing coal addition is a plot of energy contained in the sludge cake (per kg of dry sludge solids). The points of intersection of the energy supplied and energy required curves are the points of coal addition at which the sludge cake feed will sustain combustion. For coal dosage to the left of the points of intersection supplemental fuel will be required. The amount of supplemental fuel needed is represented by the difference between the energy required and energy supplied curves for the given coal addition. Coal dosages to the right of the critical points represent inputs of excess energy. This energy is not required by the combustion process.

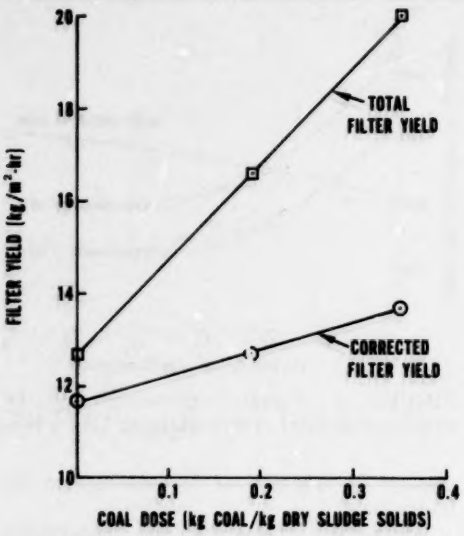

FIGURE 5. Filter yield of coal-conditioned sludge.

In a normal operation where the stack gas is at 427°C (800°F) and 75 percent excess air has been used, the energy required with no coal added is 5 162 kg-cal/kg (9 300 Btu/lb) solids. This corresponds to a 21.5 percent solids cake. The energy supplied by 1 kg of solids is 4 052 kg-cal (7 300 Btu/lb). Therefore, about 1 110 kg-cal must be supplied by addition of auxiliary fuel to maintain the combustion of 1 kg of solids under these conditions. For the 427°C (800°F) exhaust gas the autogenous point is at a coal dosage of 0.11 kg coal/kg dry sludge solids. For the 760°C (1 400°F) case the autogenous point is at 0.21 kg coal/kg dry sludge solids.

EFFECT OF PULVERIZED COAL ADDITION ON FILTER YIELD

The addition of pulverized coal in the range of dosages required to sustain sludge cake combustion effected increases, although not dramatically, in filter throughput, expressed as filter yield. Filter yield is plotted as a function of coal dosage in Figure 5. Cycle time was maintained at 4 minutes for these experiments. The total filter yield depicts the filter production in terms of total solids (sludge, conditioning chemicals, and coal) processed per square meter of filter area per hour. The corrected filter yield factors out the effect of the presence of the coal and the conditioning chemicals in the sludge cake. Since the corrected filter yield represents the amount of dry sludge solids processed per unit of filter area, it is the figure of importance.

From Figure 5, it can be seen that corrected filter yield increased a maximum of 20 percent at the relatively high coal dosage of 0.35 kg coal/kg dry sludge solids. The filter yield for the case of no coal addition was found to be 11.7 kg/m²·h (2.4 lb/sq ft·h) while the filter yield at the 0.35 coal dosage was 13.7 kg/m²·h (2.8 lb/sq ft·h). While this increase is not as significant as is the cake solids or fuel value improvement, it is, nevertheless, important. With the exhibited filter yield performance, it will not be necessary to increase plant filtration capacity to accommodate the increased solids loading attributed to the presence of the coal in the sludge feed.

EFFECTS OF CYCLE TIME

The cycle time in vacuum filtration is the amount of time required to complete one revolution of the filter drum. Cycle time is expressed in minutes per revolution (min/rev). The cycle time can be adjusted to accommodate varying sludge feed conditions. Generally, for equivalent sludge feed conditions an increased cycle time will result in a higher resultant cake solids content and a lower filter throughput. A decreased cycle time will achieve a higher filter yield at the expense of cake solids content. Several cycle times were investigated for the coal-conditioned sludge.

At a 4 min/rev cycle time the average yield was about 11.7 kg/m²·h (2.4 lb/sq ft·h). But experiments comparing the 6-, 4-, and 2-minute cycle times revealed that speeding up the drum from 6 to 4 min/rev resulted in a 12 percent increase in filter yield and that another 12 percent increase occurred for the change from the 4 to 2 min/rev cycle. No change in the cake solids occurred in the adjustment from the 6 to 4 min/rev cycle time, but the increased drum speed to 2 min/rev produced a cake with lower solids.

EFFECTS OF COAL ADDITION ON FILTRATE QUALITY

The effects of the addition of pulverized coal on the concentration of solids in the filtrate were investigated. Table IV describes the filtrate characteristics as a function of coal dose. At the thermally optimum coal

dose (0.11 kg coal/kg solids) the filtrate suspended solids (ss), chemical oxygen demand (COD), and iron content will not be greatly affected. However, if the filtration characteristics of the sludge are such that greater coal doses will be required for the combustion process, the filtrate characteristics, particularly ss, will exhibit some improvement.

The use of ferric chloride as a conditioning agent results in a filtrate with a reddish color. This color is caused by the presence of ferric hydroxide particles in the filtrate. The concentration of the ferric hydroxide in the filtrate is reduced with increasing doses of pulverized coal. This reduction in ferric particles results in a noticeably clearer filtrate with each increase in coal dose.

TABLE IV. Filtrate characteristics.

Coal Dose (kg coal/ kg dry ss)	Suspended Solids (mg/l)	COD (mg/l)	Fe (mg/l)
0	160	1 160	3.1
0.19	152	1 110	2.6
0.35	128	1 099	2.2
0.42	127	1 040	0.9

IMPLICATIONS OF COAL SIZING

As previously described, the coal used in this study was pulverized in a hammer mill. The coal used in the vacuum filtration study contained particles chiefly in the size range of 0.212 mm to 9.5 mm. Only one very basic attempt was made to determine the effect of coal particle size on filtration results. This coal sizing test was performed with a laboratory filter leaf. Three separate sizes were prepared by sieving. The coal was mixed with a liquid sludge that had been conditioned with 10 percent lime and 10 percent ferric chloride. Coal dose was 0.2 kg coal/kg dry sludge solids. Standard conditions of 4-minute cycle time with a 30 percent submersion time was used for this filter leaf test. Results are described in Table V.

The size of coal in the 0.600-mm to 0.212-mm range produced the best results on the filter leaf. The size of the coal, however, had no effect on the heat value of the conditioned sludge solids. Use of coal with the smallest size, 0.212 mm to 0.150 mm, did result in a higher cake moisture content than that obtained with the larger fractions. While one might expect that the smallest size coal would produce the best filtration results, it is conceivable that the smallest size coal in this test was not compatible with the filter media used. The relationship between coal particle size and filter media selection was not explored further in this study but could be the topic of an entire future investigation.

ESTIMATED COSTS

Coal prices in the U. S. exhibit a strong geographic dependency. Coal prices for the Midwest area (East-North Central Region) for May 1975 averaged $25.46/metric ton ($23.09/ton) or $4.25/million kg-cal ($1.07/million Btu).[5] However, this cost was based on a coal with an average heating value of 5 966 kg-cal/kg (10 749 Btu/lb). The coal used in this study was a better grade of coal with a heating value of 7 382 kg-cal/kg (13 300 Btu/lb). Using the figure of $4.25/million kg-cal ($1.07/million Btu), a projected cost can be obtained per metric ton of lumped coal in carload quantities of $31.38/metric ton ($29.46/ton). To this price for delivered lumped coal must be added the cost for reducing the particle size of the lumped coal to the functional range used in this study. These grinding costs have two components, capital and operational.

For safety, coal grinding operations require specialized equipment. To eliminate hazards of fire or dust explosions, the grinding should occur in a controlled atmosphere with proper ventilation. Special units have been developed to accomplish coal pulverization. One such unit has the capability to reduce 2.834 metric tons (3.125 tons) per hour of coal to a fine (80 percent below 230 mesh) particle size. The unit has a 45-horsepower

TABLE V. Effects of coal particle size on filter leaf results.

Coal fraction size range (mm)	0.150 to 0.212 (100 mesh)	0.212 to 0.600 (70 mesh)	0.600 to 1.180 (30 mesh)
Filter yield ($kg/m^2 \cdot h$)	19.5	21.5	18.5
Final cake solids (%)	23	25	25

motor, operates in an inert atmosphere, and uses a bag filter to collect fine particulates. The patented version of this unit has an installed price of about $102 000. For a 3.8×10^5-m³/d (100-mgd) plant requiring roughly 1 ton of pulverized coal per hour on a 24-hour basis, the amortized capital costs (20 years at 7 percent) are $2.48/metric ton ($2.25/ton) of coal processed. The pulverizer units are designed for automatic operation. However, an imputed cost for operation and maintenance of 50 percent of capital investment will be assigned. Thus, for a 3.8×10^5-m³/d (100-mgd) plant, coal grinding costs are roughly estimated to be $3.72/metric ton ($3.37/ton) of coal processed. Added to the purchase price of $31.38/metric ton ($28.46/ton), total costs associated with coal purchasing and size reduction are estimated to be $35.09/metric ton ($31.83/ton) of coal, or $4.76/million kg-cal ($1.20/million Btu). This pulverized coal would be of a much finer size than that used in the pilot plant study. It is possible that costs for achieving a larger particle size may be lower but this higher figure is used for the sake of conservatism.

Prices for fuel oil and natural gas also vary with geography. However, May 1975 average prices in the Midwest area were reported as $8.54/million kg-cal ($2.15 per million Btu) for No. 2 fuel oil and $5.95/million kg-cal ($1.50 per million Btu) for natural gas (where available).[5] Oil prices had been relatively stable at $0.082/l ($0.31/gal) for a number of months and natural gas prices are currently regulated at $0.054/m³ ($0.15/100 cu ft).

For the purpose of comparison, four fuel cases will be considered: (a) use of natural gas, (b) use of No. 2 fuel oil, (c) use of lump coal, and (d) use of pulverized coal.

In Figure 3, the y-intercept (no coal addition) of the solid content curve represents the cake solids content that would be achieved from the vacuum filter using only lime and ferric chloride as conditioning agents. This is the sludge cake that would be fed to the incinerator under normal operating conditions. From Figure 3, the cake which will serve as the basis for auxiliary fuel requirement is a cake with a solids content of 21.5 percent. From Table I, for incineration in a multiple hearth furnace at 75 percent excess air and a 427°C (800°F) exhaust gas temperature, this cake would require an input of 1.12 million kg-cal/metric ton of dry solids (3.24 million Btu/ton of dry solids) in the form of supplemental fuel. This is the amount of supplemental fuel that would be required for the addition of natural gas, fuel oil, or lumped coal. From Figure 4, only 0.11 metric tons or 0.81 million kg-cal (2.93 million Btu) in the form of pulverized coal are required to sustain combustion of 4.76 metric tons of cake in wet form (1 metric ton of sludge solids). The comparative costs for each fuel are displayed in Table VI. From this table, it is evident that projected savings from the use of pulverized coal range from considerable for the fuel oil, to significant for the lump coal. Cost savings for a 3.8×10^5 m³/d (100 mgd) plant on an annual basis are described in Table VII.

PERSPECTIVES ON ESTIMATED COSTS

Cost projections in Tables VI and VII are based on a 21.5 percent solids content cake. This is a relatively high figure for primary/activated sludge applications. In practice, final cake solids contents in the range of 15 to 20 percent can normally be expected. In any case, a lower base cake solids content will increase the advantage of the pulverized coal case over the alternative fuels.

As stated previously, costs of all fuels vary geographically. However, in almost all areas of the U. S. the relative behavior of fuel costs is such that coal is the most economical fuel.

Before installation of coal pulverization equipment at a given plant, a thorough cost

TABLE VI. Estimate of comparative costs for alternative fuels (Midwest U. S.).

Fuel	Cost/ Million kg·cal	Million kg·cal Required/Metric Ton Sludge Solids	Total Cost/ Dry Metric Ton of Sludge
Natural gas	$5.95	1.12	$6.66
No. 2 fuel oil	$8.54	1.12	$9.56
Lump coal	$4.25	1.12	$4.76
Pulverized coal	$4.76	0.81	$3.86

Note: Costs are for sludge and incinerator in Figure 4.

analysis should be made. Geographic factors and scale economics should be taken into account. In plants below 1.9×10^5 m³/d (50 mgd) in size, simple addition of lump coal, or purchase of pulverized coal may be the most economical alternative.

USE OF INCINERATOR ASH AS A DEWATERING AID

Bench-scale research completed by EPA in 1973 concerning conditioning of sludge with incinerator ash was the basis for exploring the use of coal as a filteration aid. Ash conditioning to improve filter yield and cake solids has been employed successfully with secondary sludges at Cedar Rapids and Indianapolis. Through ash addition, the quantities of chemicals needed for conditioning can be reduced significantly. Cake discharge is excellent when the sludge is conditioned with ash, and total cake solids increase substantially. Figure 6 summarizes the performance of incinerator ash in sludge conditioning.[1] Note that two parameters are improved in the ash addition process. Filter yield and total cake solids are enhanced markedly with the addition of incinerator ash. However, the incinerator "sees" only water, volatiles, and nonvolatiles. Since the ash has no heating value, and in fact requires additional heat input to raise its temperature, all volatiles are provided by the sludge solids. With higher concentrations of inert ash in the sludge feed, the ratio of volatile solids: moisture actually decreases. Therefore, as evidenced by the uppermost curve in Figure 6, the amount of energy in the feed per unit of moisture decreases with increasing ash content. Although the vacuum filter performance has been upgraded with the use of incinerator ash, the characteristics of the cake with regard to incineration have deteriorated

TABLE VII. Annual fuel costs for 3.8 $\times 10^5$ m³/d (100 mgd) plant.

Fuel	Total Annual Costs ($1 000)	Savings by Pulverized Coal Use ($1 000)	Fuel Cost/ Pulverized Coal Cost
Natural gas	215	87	1.68
No. 2 fuel oil	308	180	2.40
Lump coal	153	25	1.19
Pulverized coal	128	—	1.00

Note: Costs are for sludge and incinerator in Figure 4.

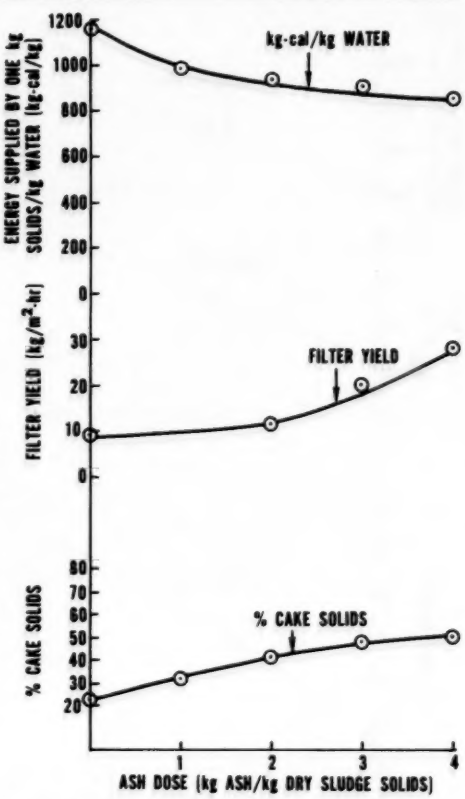

FIGURE 6. Incinerator ash performance.

and more supplemental fuel per unit of dry sludge solids will be required for combustion.

Figure 7 summarizes the filtration results for the coal addition. Note that the heat energy per unit of water increases as coal is added. Figure 8 compares calculated cake solids requirements for autogenous combustion of sludge filter cake previously conditioned with ash to the solids content required for the coal-conditioned sludge. The values in Figure 8 are for an incinerator operating with 75 percent excess air and an exhaust gas temperature of 427°C (800°F). Each increase in ash dose depletes the fuel value of the cake and hence requires a higher solids content in the filter cake. When coal is added, the cake solids content required for autogenous combustion is lower because the fuel value is enhanced and thus more fuel is available per unit of water. Adding coal

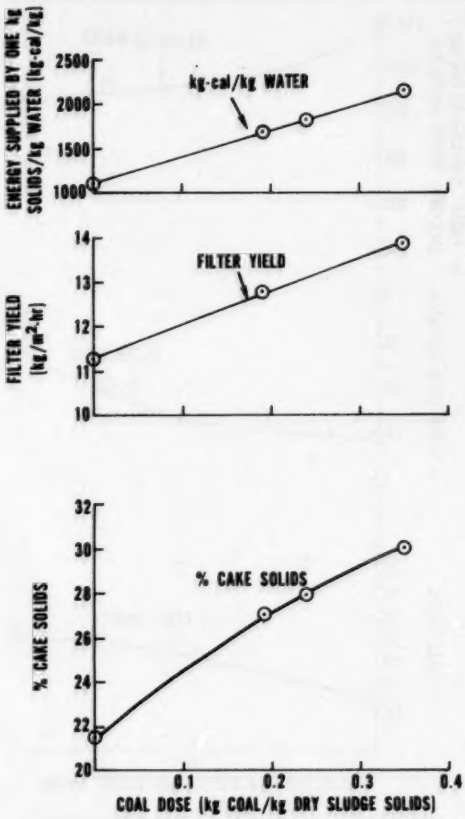

FIGURE 7. Coal performance.

to the sludge before filtration improves the fuel value of the sludge and is much the same as adding auxiliary fuel separately, but at a much lower cost since the cake quality is enhanced by the dewatering effect. The addition of auxiliary fuel has also been difficult to control in many incinerators because the feed (sludge filter cake) is not consistent. Nonuniformity in fuel value results in localized hot spots. The thermal transients from these hot spots can result in rabble arm and interior shaft damage, necessitating costly repairs. Finely distributing the pulverized coal throughout the sludge cake feed should result in a more uniform temperature distribution in the incinerator.

DISCUSSION

A treatment plant now considering incineration for sludge disposal will undoubtedly choose a dewatering method that will produce a sludge cake requiring no auxiliary fuel for combustion. Many of these plants will choose a pressure filter or belt press. But for plants which are now incinerating and using vacuum filtration to dewater the sludge, the addition of pulverized coal to the sludge feed may reduce the high costs of axuiliary fuel. Coal can be added directly to the sludge, or a similar effect can be achieved by adding coal to the wastewater. It is claimed that the addition of coal to the wastewater yields other benefits in wastewater treatment.[6]

This research was performed at one plant with one sludge. The ratio of coal:sludge is a variable depending on the filterability of the particular sludge at a particular plant. If the sludge at a plant normally produces a 15 percent solids cake, then the dose of coal required to achieve autothermal conditions may be considerably higher than that found in this study. However, the cost of oil for auxiliary fuel to burn a 15 percent solids cake will also be very high and therefore a cost savings will still be realized despite the large amount of coal required.

Another way to reduce costs is to use a lower grade coal. Coal quality is measured by heating value, volatile content, and type and nature of the ash. If other things are equal, the cost of coal is roughly proportional to its heating value. If, as expected, a low-grade coal exhibits the same effect on dewatering as a high grade coal, the cost savings by using a low-grade coal can be substantial. This is true because, as Figure 4 demonstrates, the use of a higher proportion of coal produces a drier cake. If, for example, heating value (and cost) of a low-grade coal is

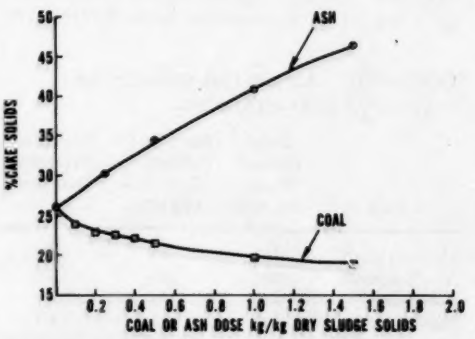

FIGURE 8. Calculated cake solids requirements for autogenous combustion.

20 percent less than for a high-grade coal, it is not necessary to add 20 percent more of the low grade coal to reach the autothermal point because the cake is drier and needs less supplemental energy.

CONCLUSIONS AND RECOMMENDATIONS

It is now necessary to apply the results of this research study to full-scale processes. Some cities are becoming somewhat desperate in their search for sources of fuel other than natural gas or oil. Coal seems to be most feasible alternative at this time. If a wastewater treatment plant obtains lump coal in carload quantities, the coal must be ground to the effective size at the plant. This process has many dangerous facets and must be controlled by experienced personnel. After grinding, the coal must be stored; because coal strikes are a constant threat, sufficient storage for a reasonable time is needed.

Regardless of the type of fuel used at an incineration plant, a bomb calorimeter is a worthwhile investment. Frequent heating value readings for the incinerator feed will enable the plant operators to more closely control the use of supplemental fuel in the combustor.

SUMMARY OF RESULTS

The premise for this study of the addition of pulverized coal to liquid sludge is that the efficiency and cost of sludge incineration is largely a function of the performance of the dewatering process. In most cases involving secondary sludges, the dewatering operation does not yield a sludge cake that is sufficiently high in solids and volatiles to provide autogenous combustion to proceed. Consequently, sludge incineration is heavily dependent on consumption of supplementary fuel, which is now both costly and difficult to obtain.

Calculated heat balances for the multiple hearth incinerator with 427°C (800°F) stack gas yielded a requirement of 25.9 percent cake solids content for the sludge tested to sustain autogenous combustion. With no coal addition, the vacuum filter produced only a 21.5 percent solids content cake.

Additions of pulverized coal with a median particle size of 28 Tyler mesh to the liquid sludge prior to vacuum filtration resulted in significant improvements in filter performance. Table VIII is a capsule summary of filtration performance and cake composition as a function of coal addition. Autogenous combustion could be achieved with a coal dosage of 0.11 kg coal/kg dry sludge solids.

TABLE VIII. Capsule summary of effects of coal addition.

Coal Dosage	0	0.1 kg Coal/ kg Dry Solids	0.3 kg Coal/ kg Dry Solids
Cake solids (%)	21.5	25	29.3
Corrected filter yield ($kg/m^2 \cdot h$)	11.2	12.2	13.7
Energy supplied by 1 kg solids/ kg water (kg·cal/kg)	1 110	1 499	2 054

The most significant effect of the pulverized coal conditioning was the increase in cake solids. Filter yield increased but not as significantly as did cake solids or input energy/kg contained moisture. The significant increase in cake solids caused by coal addition and the slight increase in filter yield (on a sludge solids basis) demonstrated that adding coal to the sludge before filtration would require less coal to achieve autogenous incineration than adding coal to the sludge cake after filtration.

In comparing costs of four separate fuels (natural gas, fuel oil, lump coal, and pulverized coal), the pulverized coal was found to be an economical alternative to the less available fuel types. Fuel cost estimates for adding pulverized coal were 40 percent below the natural gas case and 58 percent lower than the case where No. 2 fuel oil was used.

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